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THE DOUBLE-LINED SPECTROSCOPIC BINARY IOTA PEGASI

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Low-noise Reticon observations of ι Peg at 6430 Å reveal weak, well-defined lines of the secondary. We have determined the secondary velocity curve for the first time and have redetermined the primary velocity curve. The orbit is circular with $K_A = 48.1 \pm 0.2$ km s^{-1} and $K_B = 77.9 \pm 0.3$ km s^{-1} and corresponding minimum masses of $1.31 \pm 0.02\ \mathfrak{M}_\odot$ and $0.81 \pm 0.01\ \mathfrak{M}_\odot$ for components A and B, respectively. These minimum masses are sufficiently close to the expected actual masses of this main-sequence pair as to suggest a reasonable prospect of eclipses, in spite of the relatively long period of 10.2 days.

The $v \sin i$ of the primary is 7 ± 2 km s^{-1} and is the same, to within the uncertainties, as the $v \sin i$ of 6.5 ± 0.5 km s^{-1} for synchronous rotation. The $v \sin i$ of the secondary is 9 ± 3 km s^{-1} and is significantly greater than the $v \sin i$ of 4.5 km s^{-1} estimated for synchronous rotation.

The spectral type of the secondary is estimated to be G8 V. The 6707 Å Li I line is measured in both the primary and secondary. The line is unusually strong in the secondary indicating that the system is very young.

Key words: spectroscopic binaries—orbital elements—lithium abundances—age

I. Introduction

The star ι Pegasi (HR 8430 = HD 210027, $\alpha = 22^h02^m21^s$, $\delta = 24°51'$ (1900), $V = 3.76$, spectral type = F5 V) was discovered by Campbell (1899) to be a single-lined spectroscopic binary. Curtis (1904) computed the first set of orbital elements. Several other studies have been made including those of Petrie and Phibbs (1949) and Abt and Levy (1976). Each of these last two orbital-element determinations has been called definitive in the orbital-element catalogs of Batten (1967) and Batten, Fletcher, and Mann (1978), respectively.

Herbig (1965) noted in a study of the lithium abundances of solar-type stars that the secondary of ι Peg was visible at red wavelengths. We report low-noise Reticon observations at 6430 Å which clearly show the secondary spectrum. These observations have been used to determine the velocity curve of the secondary for the first time, redetermine the primary velocity curve, and discuss the properties of both components.

II. Observations and Orbit

From 1977 through 1982, 32 observations which showed double lines and three which showed single lines (Table I) were obtained with the McDonald Observatory 2.7-m telescope, coudé spectrograph, and a 1024-element Reticon silicon photodiode array (Vogt, Tull, and Kelton 1978). All but three of the observations were obtained at a wavelength centered at 6430 Å. Of the other three observations, one was centered at 6685 Å and included the 6707 Å Li I line, while the other two were centered at 8800 Å and 8710 Å. The observations covered 100 Å at a dispersion of 4.4 Å mm^{-1} with a resolution of 0.24 Å or 0.36 Å corresponding to a two- or three-diode projected slit width, respectively. The signal-to-noise ratios of the observations range from 200:1 to 300:1. The observations were reduced relative to the radial-velocity standard star ι Piscium using cross-correlation techniques as described by Tomkin (1983). The adopted velocity of ι Psc is 5.3 km s^{-1} (Pearce 1955).

The Dominion Astrophysical Observatory observations obtained between 1935 and 1938 (Petrie and Phibbs 1949) were used to improve the value of the period. This value was fixed and separate solutions of the orbital elements of the primary and secondary were made with only the McDonald data. From a comparison of the standard deviations of these solutions the secondary velocities were given one-half the weight of the primary velocities. A simultaneous solution of the primary and secondary velocities was computed with a differential-corrections computer program described by Barker, Evans, and Laing (1967), which was modified for the double-lined case. The three blended observations have been given zero weight. The eccentricity of this solution is 0.0033 ± 0.0037. Thus, according to the precepts of

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Table I

Observations of ι Peg

HJD 2400000+	Phase	V_A km s^{-1}	$(O-C)_A$ km s^{-1}	V_B km s^{-1}	$(O-C)_B$ km s^{-1}
43445.532	0.449	-50.4	0.8	69.2	0.7
43446.569	0.551	-52.8	-1.6	67.4	-1.1
43447.533	0.645	-35.7	-0.7	42.3	0.1
43448.599	0.750	- 7.3	-1.6	—	-
43449.540	0.842	20.6	-0.0	-46.1	1.9
43450.524	0.938	39.6	0.7	-77.0	0.7
43451.610	0.044	41.0	0.3	-79.1	1.4
43620.984	0.628	-38.6	0.2	51.0	2.6
43740.955	0.375	-39.5	0.1	49.3	-0.4
43742.874	0.563	-50.0	-0.1	66.4	0.1
43743.796	0.654	-32.4	0.6	41.7	2.8
43770.689	0.287	-16.8	-0.3	10.9	-1.4
44039.917	0.648	-35.9	-1.6	40.9	-0.2
44087.854	0.342	-32.0	-0.3	37.3	0.4
44094.911	0.033	41.6	0.1	-82.3	-0.4
44095.774	0.117	30.0	-0.1	-63.1	0.2
44113.758	0.878	28.8	-0.3	-61.9	-0.2
44115.628	0.061	38.0	-1.0	-79.6	-1.8
44116.739	0.170	17.2	-0.5	-42.1	1.1
44119.750	0.465	-54.0	-1.5	71.1	0.6
44120.801	0.568	-50.8	-1.4	65.8	0.3
44143.558	0.796	7.3	-0.8	-25.2	2.5
44147.559	0.188	11.5	-1.3	-36.1	-0.8
44176.548	0.026	43.0	1.1	-80.7	1.8
44177.586	0.128	27.5	-0.4	-59.4	0.3
44179.736	0.338	-30.3	0.5	35.7	0.3
44186.547	0.005	41.6	-0.9	-83.3	0.2
44214.535	0.746	- 7.7	-0.8	—	-
44215.518	0.842	19.5	-1.2	-48.4	-0.4
44216.518	0.940	37.9	-1.2	-79.2	-1.2
44472.817	0.035	42.1	0.7	-79.8	1.8
44896.722	0.541	-51.1	0.9	71.2	1.4
45308.585	0.868	27.4	0.4	-57.1	1.2
45324.577	0.434	-48.8	0.8	66.9	1.1
45327.542	0.724	-11.3	1.9	—	-

Lucy and Sweeney (1971), a double-lined solution with $e = 0$ has been adopted. Orbital elements with this assumption are listed in Table II. Figure 1 shows the computed velocity curves compared with the observations. Phases are computed from T_0, the time of the maximum positive radial velocity of the primary component.

Table II

Orbital Elements of ι Peg

$P = 10.213033 \pm 0.000013$ days (m.e.)

$T_0 = 2445320.1423$ HJD

$e = 0$ (assumed)

$\gamma = -5.5 \pm 0.2$ km s^{-1}

$K_A = 48.1 \pm 0.2$ km s^{-1}

$K_B = 77.9 \pm 0.3$ km s^{-1}

$a_A \sin i = 6.75 \pm 0.03 \times 10^6$ km

$a_B \sin i = 10.95 \pm 0.05 \times 10^6$ km

$M_A \sin^3 i = 1.31 \pm 0.02\ M_\odot$

$M_B \sin^3 i = 0.81 \pm 0.01\ M_\odot$

$M_A/M_B = 1.62 \pm 0.01$

III. Rotational Velocities, Radii, and Masses

To determine the projected rotational velocity of the primary, the full-width half-maxima of several lines in the 6430 Å region were measured in each of two Reticon observations. The square of the average of the full-width half-maxima of several neon comparison lines was subtracted from the square of the observing widths to correct for the instrumental profile. By measuring the full-width half-maxima of the same lines in II Peg and HR 1099 and comparing these to the projected rotational velocities determined for these stars by Vogt (1981) and Vogt and Penrod (1982), a relationship between the instrumentally corrected full-width half-maxima and line broadening was determined. From line-profile modeling Soderblom (1982) determined macroturbulent velocities which ranged from 2.5 to 3.3 km s^{-1} for 20 solar-type stars. He concluded that these results were consistent with a macroturbulent velocity of 3 km s^{-1}, independent of spectral type or age. Assuming a macroturbulence of 3 km s^{-1}, $v \sin i$ of the primary is 7 ± 2 km s^{-1} (estimated error) in excellent agreement with the values of Soderblom (1982), 6.5 km s^{-1}, and Kraft (1967), 7 km s^{-1}. Of the three values, Soderblom's (1982) is probably the most accurate. Assuming a radius of $1.3 \pm 0.1\ R_\odot$ for the primary, which is the average radius for components of eclipsing systems with reliable solutions (Popper 1980) and the same spectral type, F5 V, as the primary, we estimate $v \sin i = 6.5 \pm 0.5$ km s^{-1} for synchronous rotation. Thus, the rotation of the primary is synchronous to within the uncertainties.

Similarly, three lines of the secondary were measured in the same two Reticon observations. The resulting value of $v \sin i$ for the secondary is 9 km s^{-1}. The estimated uncertainty of 3 km s^{-1} is larger than the uncertainty for the primary's $v \sin i$ because, although an attempt was made to avoid possible blended lines and the full-width half-maxima of the various lines are quite consistent, the lines of the secondary are only 5% deep at most and, therefore, blending with weak primary lines is a potential problem. The secondary spectral type of G8 V, determined in the following section, leads to a secondary radius of $0.9\ R_\odot$ (Allen 1973) and a $v \sin i$ of 4.5 km s^{-1} for synchronous rotation. Thus, the rotation of the secondary is significantly faster than synchronous.

From the orbital solution the minimum mass of the F5 V primary is $1.31\ \mathfrak{M}_\odot$. Such a mass is similar to the components of eclipsing systems with F5 V spectral

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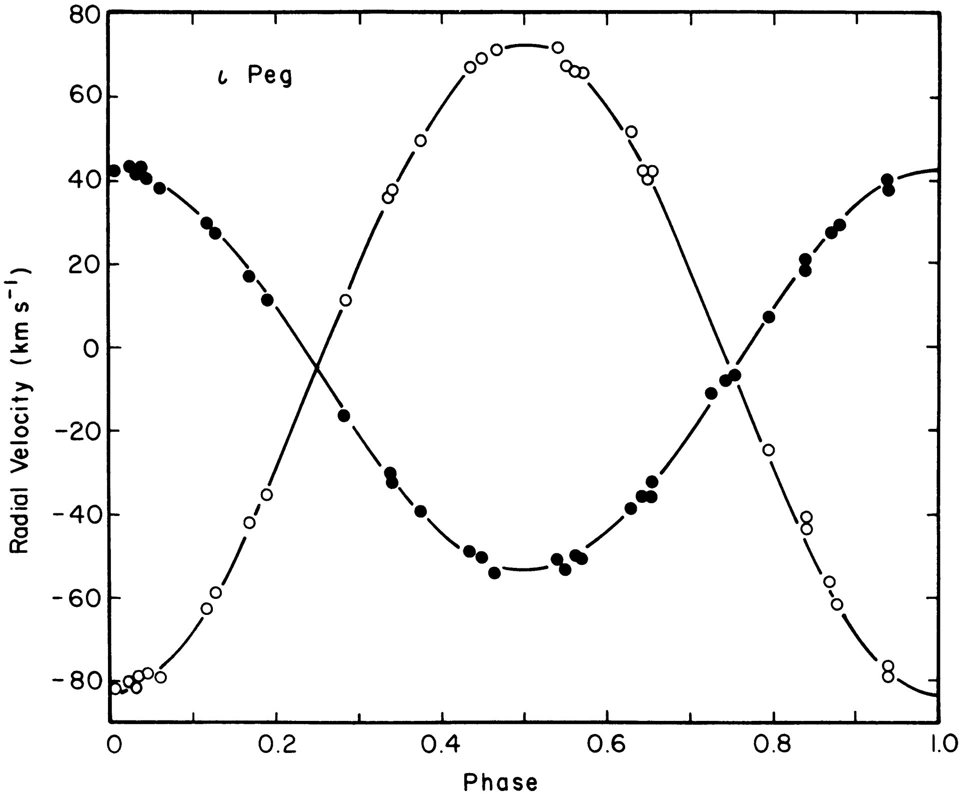

FIG. 1—The radial-velocity curves and observations of ι Peg. Dots = primary, open circles = secondary. Phase is computed from T_0.

types (Popper 1980) which have masses ranging from 1.23 $\mathfrak{M}_\odot$ to 1.37 $\mathfrak{M}_\odot$. This minimum mass suggests that despite the moderately long period of 10.2 days, eclipses are a reasonable possibility. With the estimated primary and secondary radii of 1.3 $R_\odot$ and 0.9 $R_\odot$, respectively, the inclination of the system must be at least 85° for eclipses to occur. With $i = 90°$ a total eclipse from first to fourth contact would last 6.8 hours. A possible primary eclipse would occur at phase 0.25 while a possible secondary eclipse would occur at phase 0.75. Although we have spectroscopic observations near phase 0.75, it is not possible to determine from these observations whether or not any eclipses occur. Because the orbit is circular, the predicted times of possible eclipses should be quite accurate. Very few main-sequence stars with spectral types later than the sun are known to be eclipsing. Thus, if the stars do eclipse, the determination of the mass and radius of the secondary would be particularly important.

As has already been noted, the minimum mass of the primary is about what would be expected for its spectral type. The value of 0.81 $\mathfrak{M}_\odot$ for the secondary is consistent with the value of 0.78 $\mathfrak{M}_\odot$ tabulated by Allen (1973) for a K0 V star. However, McClure (1982) has pointed out that young solar-type stars would be expected to be more massive than the values listed by Allen (1973) since the mass-luminosity relation of such stars would be 0.8 mag below that of a field-star relation. Thus, if the secondary is a young G8 V star, as will be concluded in the following sections, it should be somewhat more massive than the observed minimum value. A mass of 0.85 $\mathfrak{M}_\odot$ requires an inclination of 80° and results in a mass of 1.38 $\mathfrak{M}_\odot$ for the primary; a value which is just consistent with eclipsing binary results (Popper 1980).

IV. The Secondary

Herbig (1965) detected the secondary spectrum on 4 Å mm^{-1} plates obtained at red wavelengths. Figure 2 shows a 30 Å portion of two Reticon observations near opposing quadratures in which lines of the secondary, although weak, are quite obvious and well-defined.

A determination of the minimum magnitude difference can be made with Petrie's method (1939). Measurement of the line strengths of four sets of lines in the 6430 Å region in two observations near opposing quadratures gives an average magnitude difference ΔR = 1.60 ± 0.04 mag. The lines which were measured are Fe I and Ca I lines having low excitation potentials and are, therefore expected to be substantially stronger in the secondary. Since no correction was made for this effect, the magnitude difference is a minimum one. From Allen

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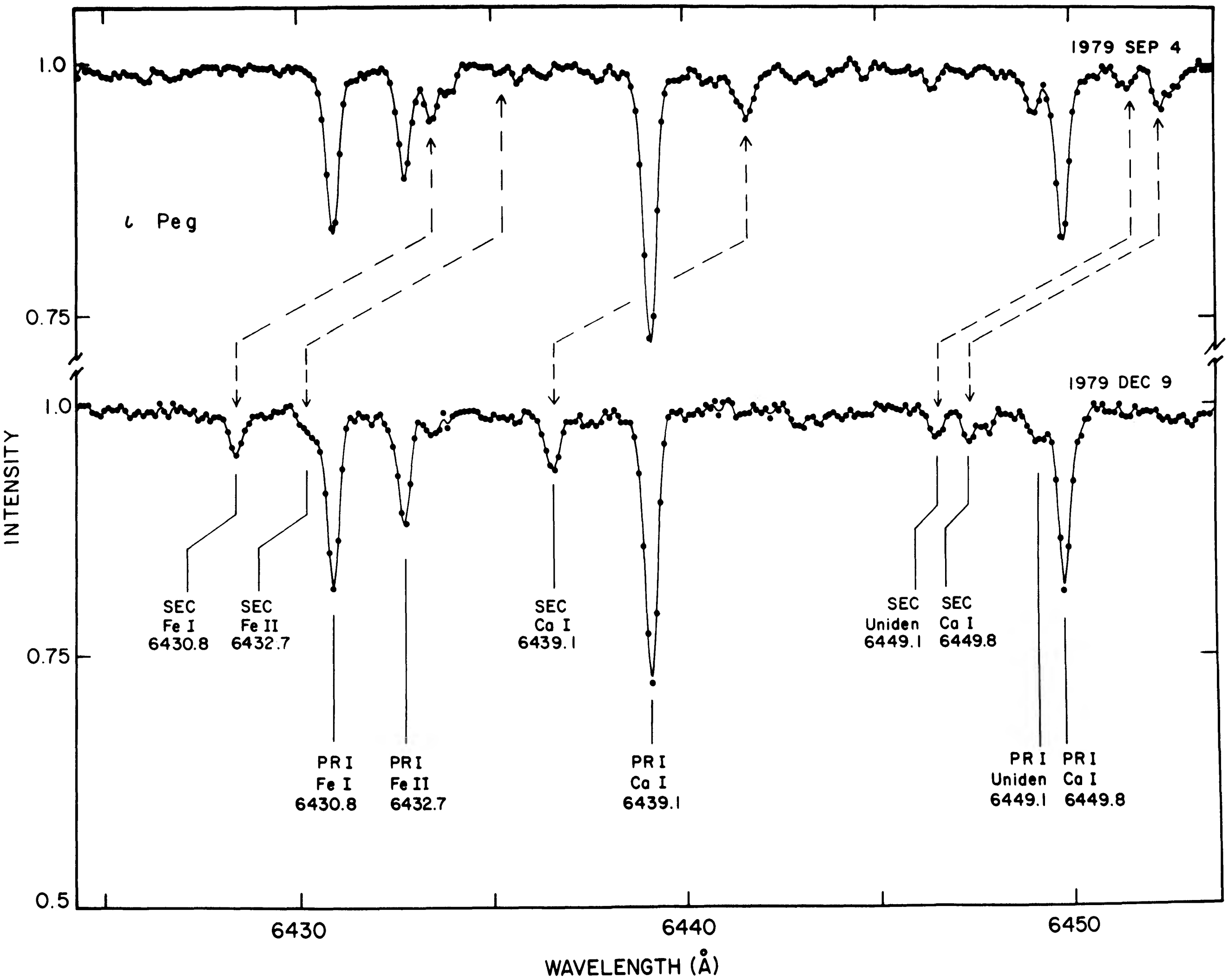

FIG. 2—A portion of two Reticon observations of ι Peg in which the secondary spectrum is blue- and redshifted with respect to the primary spectrum. The wavelength scale is for the primary and the intensity scale is expanded. Note the weakness of the 6432.7 Å Fe II line in the secondary. The line through the points is a smoothed fit determined from a filtered power spectrum.

(1973) this minimum magnitude difference suggests that the spectral type of the secondary is G5 V or later.

The spectral type of the secondary also may be estimated by comparing the observed magnitudes with the combined magnitudes computed from the spectral classification, color relation tabulated by Johnson (1966). Table III shows the observed *UBVRIJK* magnitudes (Johnson et al. 1966) compared with the best computed combinations. The spectral type of the primary was held constant while ΔR and the spectral type of the secondary were varied. Unfortunately, the secondary is a minor contributor to the combined magnitude of the system at all wavelengths, even in the infrared. Making the secondary fainter approximately compensates for making it later in spectral type. As a result, good fits to the observed magnitudes can be found for spectral types from G5 V to K0 V with ΔR values from 2.0 to 3.0 mag.

The primary of ι Peg is an F5 V MK standard and has solar abundances (Herbig 1965). It is possible to put further limits on the spectral type and magnitude difference by comparing the corrected line strengths of the secondary computed from assumed magnitude differences with the line strengths of a star whose spectral type is close to that of the secondary and which was observed with the same instrument and settings. The strongest lines of the secondary in the 6430 Å region are 5% deep, while the same lines in ϵ Eridani (K2 V) are 55% to 60% deep. Thus, the observed line depths are approximately a factor of 11 smaller than in ϵ Eri. This implies a primary to secondary light ratio of 10 or $\Delta R = 2.5 \pm 0.3$ (estimated uncertainty). An implicit assumption in the above line of reasoning is that the lines in the spectrum of the secondary itself are the same depth as in ϵ Eri. Small abundance and spectral-type differences between the two stars must cause differences in their line depths. But, because the lines used are saturated, the variation of their depth with abundance and spectral-type differences is slow, so the differences of depth are small and the assumption probably valid. The uncertainty of this magnitude difference is estimated from the fact that a magnitude difference of 2.0 requires the line depths of the secondary to be increased by a factor of seven while a magnitude difference of 3.0 requires them to be increased by a factor of 17. The $\Delta R = 2.5 \pm 0.3$ plus the results of Table III show that the secondary has a probable spectral type of G8 V. Thus, with $\Delta V = 2.68$ and a trigonometric parallax of 0.″074 (Jenkins 1963) the absolute visual magnitudes are 3.20 and 5.88 mag for the primary and secondary, respectively.

V. Age

Since the 1960s it has been believed that for solar-type stars the abundance of lithium (Herbig 1965), the strength of Ca II H and K emission lines (Wilson 1963), and rotational velocity (Kraft 1967), in general, decrease with time. However, if a star is part of a close binary, the proximity of the second star can substantially change the Ca II emission strength and rotational velocity as, for example, in the RS Canum Venaticorum binaries. Thus, of the three spectroscopically observable parameters the lithium abundance is usually the best calibrator of age in a solar-type close binary.

Recently, Duncan (1981) made an extensive new study of the relationship between lithium abundance, Ca II emission, and age. He concluded that for most solar-type stars there is a reasonably good correlation between these parameters although there are some exceptions.

The lithium abundance of the primary has been determined previously by Herbig (1965), Conti and Danziger (1966), and Duncan (1981). Although the presence of the lithium line of the secondary was mentioned by Herbig (1965), the abundance of the secondary was not determined nor, presumably, was the abundance of the primary corrected for the presence of the secondary continuum. From a Reticon observation centered near the lithium wavelength and having a signal-to-noise ratio of over 200:1, the abundances of both the primary and secondary have been determined. Uncorrected for duplicity, the equivalent widths of the primary and secondary are 75 mÅ and 19 mÅ, respectively. For comparison, Duncan (1981) found an equivalent width of 47 mÅ and Herbig (1966) measured an equivalent width of 69 mÅ. Assuming a magnitude difference of 2.5 mag, the equivalent widths must be multiplied by factors of 1.1 and 11 for the primary and secondary, respectively. The resulting equivalent widths are 83 mÅ and 209 mÅ. The best and most-thorough treatment of the lithium abundance problem has been done by Duncan (1981) so his relationship between equivalent width and abundance will be utilized. Assuming $\log T_e = 3.795$ and $\log g = 4.07$ for the primary (Duncan 1981), from Duncan's Figure 1 its lithium equivalent width corresponds to $\log n(\mathrm{Li}) = 2.9$ (based on the total of all atoms equals 12). This is slightly greater than the zero-age main-sequence (ZAMS) value determined by Duncan (1981). Unfortunately, as Duncan (1981) points out, the lithium depletion time scales for F5 V and F6 V stars are very long and indeterminate from current cluster data. Thus, in order to estimate the age of the system the abundance of the secondary must be determined.

Table III

Comparison of Observed and Computed Magnitudes

Combination	U	B	V	R	I	J	K
Observed	4.17	4.20	3.76	3.36	3.11	3.00	2.65
F5 V + G5 V, ΔR = 2.0	4.25	4.23	3.78	3.36	3.10	2.94	2.65
F5 V + G8 V, ΔR = 2.5	4.24	4.21	3.77	3.36	3.10	2.94	2.65
F5 V + K0 V, ΔR = 3.0	4.24	4.22	3.78	3.36	3.11	2.95	2.65

Because the secondary line is weak, an estimate of the uncertainty in this abundance is important. Estimates of uncertainties of the magnitude difference, ± 0.3, and equivalent-width measurement of the secondary feature, ± 25%, lead to an estimated uncertainty of ± 37% in its equivalent width or an equivalent width ranging from 131 mÅ to 287 mÅ. This relatively large equivalent width can be checked by comparing it with the equivalent width of the Ca I line at 6717 Å. In fact in the past the lithium abundances of a number of stars have been determined relative to calcium using this 6717 Å Ca I line. The lithium and calcium lines of the secondary have nearly identical line depths and the uncorrected calcium equivalent width is 17 mÅ or 187 mÅ ± 69 mÅ when the magnitude difference correction is applied. The Ca I line in the solar spectrum has an equivalent width of 120 mÅ (Moore, Minnaert, and Houtgast 1966). Thus, the Ca I equivalent width of the secondary is greater than that in the sun as expected for a star of later spectral type. Since the lithium line of the secondary is at least as strong as the calcium line, an equivalent width of at least 120 mÅ is expected. If a G8 V spectral type is assumed for the secondary, then $\log T_e = 3.738$ (Hayes 1978) and the equivalent width correpsonds to $\log n(\mathrm{Li}) = 2.6 \pm 0.6$, where the uncertainty corresponds to the minimum and maximum values of the equivalent width. Increasing the gravity and /or the temperature increases the abundance. This is a very large abundance for such a late-type star. Such an abundance indicates that the system is very young and has an age similar to that of the Pleiades cluster, about 8×10^7 years (Patenaude 1978). Even the large uncertainties do not make the system as old as the Hyades cluster, age about 6×10^8 years (Patenaude 1978).

The system has a Strömgren δc_1 index of 0.006 (Crawford 1975) indicating that it is very close to the ZAMS. This result is consistent with the very young age deduced from the lithium abundance of the secondary.

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